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Numerical simulation study of spontaneous combustion in goaf based on non-Darcy seepage

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Abstract

In order to study the influence of non-Darcy seepage on spontaneous combustion in goaf, seepage tests were conducted in three groups of broken rocks which were different average particle sizes, and then the test data were processed by non-Darcy seepage equation. So that the equations of non-Darcy permeability coefficient K with porosity n and particle size d, non-Darcy flow factor β with the n and the d were achieved. On the basis of these equations, the paper analyzed the influential factors of the spontaneous combustion in goaf, and then established the spontaneous combustion mathematical model on the coupling of air flow field, oxygen concentration field and temperature field on moving coordinates. According to the model, the calculating software was programmed by VB6.0 to obtain the oxygen concentration distribution map and the residual coal temperature distribution map in goaf. The results are of theoretical and practical significance to prevent spontaneous combustion in goaf.

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Keywords: non-Darcy seepage; spontaneous combustion; numerical simulation; permeability coefficient; non-Darcy seepage factor

1. Introduction

Spontaneous combustion of the residual coal in goaf is one of the severest disasters in coal mine production [1]. Based on the coal oxygen compound theory and the Darcy's law, scholars both at home and abroad have established the spontaneous combustion mathematical model of goaf with immobile coordinates [2-4]. However, this mathematical model is an astable partial differential equation group with

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moving boundary which makes the model very difficult to be solved. In addition, the gas flow in goaf is considered to be non-Darcy seepage. The mathematical model established by Darcy's law will cause certain error. In order to solve these two problems, this paper established the spontaneous combustion model of goaf based on non-Darcy seepage, using mobile coordinates to deal with the moving boundary problem [5-6].

2. The broken rock percolation test

From macroscopic view, the goaf space is so large that the broken rocks in it can be seen as continuous porous medium for analysis [5]. In goaf, laminar flow coexists with transitional flow and turbulent flow. Therefore, the gas flow in goaf does not completely obey the Darcy's flow. The permeability coefficient is an important parameter for the study of broken rock seepage in goaf, which is related to the porosity and the particle size of broken rock. In order to obtain the fluid seepage law in broken rock, the broken rock percolation tests have been completed with seepage instruments which match MTS815.02 servo-machine [7-9], and then based on the similarity principle of fluid, the law was applied into the goaf.

In the seepage tests, three groups of broken rocks which respectively was the average particle size of 1.125mm, 2.25mm and 4.5mm are used. The same grit rock sample was loaded into permeation apparatus. After that the axial displacements were controlled to make the rock sample porosity respectively reach 0.3, 0.2 and 0.1, and then in each axial deformation three different seepage velocity were set up separately for 3.12×10^{-5}m/s, 6.25×10^{-5} m/s and 9.38×10^{-5} m/s. The test data was shown in table 1. The seepage velocity and the pore pressure gradient, obtained from the same porosity and particle size, was separately done linear fitting and nonlinear fitting. Taking the rock sample of the average granularity 2.25 mm and the porosity 0.2 for example, the fitting curve was shown in Fig. 1.

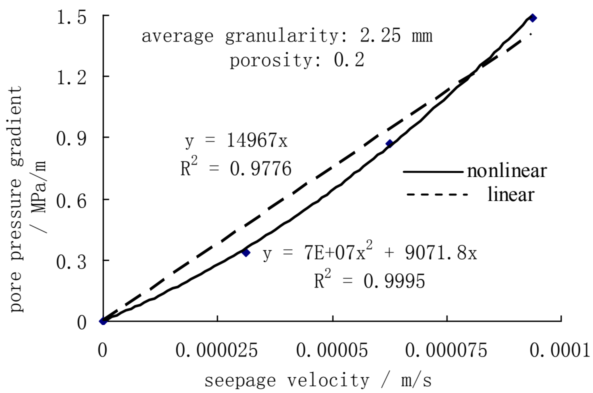

Fig.1 Fitting of seepage velocity and pore pressure gradient

In Fig.1, the correlation coefficient of the nonlinear fitting is bigger than that of the linear fitting, which is proved that the relationship of seepage velocity and pore pressure gradient is more suitable for Forchheimer type non-Darcy seepage equation. The equations from the nonlinear fitting were processed by Formula (1) to obtain the non-Darcy permeability coefficient K and the non-Darcy flow factor β. The specific data are in Table 1.

Forchheimer type non-Darcy seepage equation can be expressed as:

$$J = \rho\beta v^2 + \frac{\rho g}{K} v \tag{1}$$

The K in above is expressed as:

$$K = \frac{k\rho g}{\mu} \tag{2}$$

Where, J is the pore pressure gradient, Pa/m; ρ is the fluid density, kg/m^3; g is the gravity acceleration, N/kg; β is the non-Darcy flow factor, m^{-1}; v is the seepage velocity, m/s; K is the Non-Darcy permeability coefficient, m^2/(Pa·s); k is the permeability, m^2; μ is the fluid dynamic viscosity coefficient, Pa·s.

Table 1. Seepage characteristics of rock samples

Average granularity 10^{-3}m/s	Porosity	Seepage velocity 10^{-5}m/s	Pore pressure gradient M Pa/m	Permeability coefficient 10^{-6}m^2/(Pa·s)	Non-Darcy flow factor β 10^{10}m^{-1}
4.5	0.3	0	0	2.342	0.9
		3.125	0.127		
		6.251	0.308		
		9.377	0.467		
	0.2	0	0	1.493	2
		3.125	0.229		
		6.251	0.452		
		9.377	0.739		
	0.1	0	0	0.489	4
		3.125	0.722		
		6.251	1.36		
		9.377	2.278		
2.25	0.3	0	0	2.075	2
		3.125	0.158		
		6.251	0.372		
		9.377	0.598		
	0.2	0	0	1.080	7
		3.125	0.338		
		6.251	0.871		
		9.377	1.490		
	0.1	0	0	0.303	20
		3.125	1.486		
		6.251	2.359		
		9.377	4.600		
1.125	0.3	0	0	1.878	2
		3.125	0.157		
		6.251	0.418		
		9.377	0.638		
	0.2	0	0	0.956	7

		3.125	0.325		
		6.251	0.704		
		9.377	1.080		
	0.1	0	0	0.251	40
		3.125	1.662		
		6.251	4.065		
		9.377	7.391		

By the data results in Table 1 being fitted, both the Permeability coefficient K and non-Darcy flow factor β were related to porosity n and particle size d, which was shown in Table 2.

Table 2. Fitting equations of the penetration parameters

Seepage parameters	Equation	Correlation coefficient
K	$K=3.8\times10^{-5}n^{1.47}d^{0.19}$	0.9859
β	$\beta=1.3\times10^{6}n^{-2.06}d^{-1.16}$	0.9810

3. The spontaneous combustion mathematical model of goaf

There are lots of hypotheses on coal hypergolic mechanism, in which the most authorized one is coal oxygen compound theory [10]. Lots of crack generated in original coal by mining influence get coal internal surface increase largely, where oxygen in air proceed physical absorption, chemical adsorption and chemical reaction in sequence; adsorption and reaction give out heat; if heat can't be emitted timely, heat will amass and get coal temperature rise; meanwhile temperature increment accelerate reaction of coal and oxygen which will bring more heat; in such continually auto acceleration make coal temperature rise continuously and then reach to coal kindling temperature, so spontaneous combustion occurs. Therefore, spontaneous combustion in goaf is the result of the mutually coupling of gas seepage velocity, oxygen concentration and temperature in goaf.

3.1 Moving coordinate system

With working face advancing, the model established with moving boundary in immobile coordinates is an unsteady partial differential equation group which is very difficult to be resolved. According to the character of goaf dynamic advancing, the idea about establishing moving coordinates system which is shown in Fig. 2 is put forward. Took the midpoint of working face roof tangent as coordinates system's zero point, goaf deepening heading as x-axis positive direction, working face ascending heading as y-axis direction. The coordinates system moved with working face advancing. The relationship between moving coordinate system (x' , y') and static coordinate system (x , y) is shown in Formula (3).

$$\begin{cases} x' = x + v\tau \\ y' = y \end{cases} \tag{3}$$

Where, v is the average advance speed of working face, m/s; τ is times, s.

Compared with the gas seepage velocity in goaf, the average advance speed of working face is very small, so mobile coordinate has a major influence on the residual coal temperature field, and the effect for the others fields can be neglected.

3.2. Assumption condition

(1) The goaf internal control unit contains enough float coal and rock, which constitute the porous medium structure. Relatively to the goal, the control unit is small enough so that it can be regarded as a point; (2) in Fig. 2, Γ_2, Γ_3 and Γ_4 are the real boundaries of goaf, Γ_5, Γ_6, Γ_7, Γ_8, Γ_9 and Γ_{10} are the extended boundaries for the numerical simulation of residual coal temperature field. Except heat generated by the residual coal oxidized, there are not other heat sources existing within the boundaries.

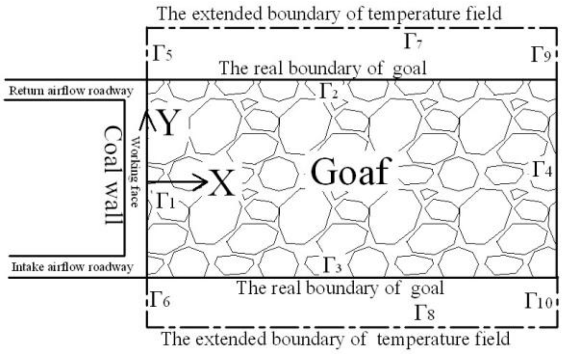

Fig. 2. Area and boundary condition of the seepage flow in goal

3.3. Spontaneous combustion mathematical model

Relatively to the length and width of goaf, the collapse height of the coal-rock in goaf is very small. Therefore, the goaf can be regarded as a two-dimensional porous media seepage field. Similarly, the oxygen diffusion in goaf also can be simplified as a planar spread motion.

(1) The flow field equation of goaf is established based on mass conservation equation and Forchheimer type non-Darcy seepage equation:

$$\begin{cases} \dfrac{\partial(\rho_g v_x)}{\partial x} + \dfrac{\partial(\rho_g v_y)}{\partial y} = 0 \\ v_x = \dfrac{g}{2K_x\beta}\left(-1 + \sqrt{1 - \dfrac{4K_x^2\beta}{\rho_g g^2}\dfrac{\partial p}{\partial x'}}\right) \\ v_y = \dfrac{g}{2K_y\beta}\left(-1 + \sqrt{1 - \dfrac{4K_y^2\beta}{\rho_g g^2}\left(\dfrac{\partial p}{\partial y'} + \rho g \sin\alpha\right)}\right) \end{cases} \tag{4}$$

Where, K_x、K_y is the permeability coefficient in x, y direction, m/s. For a point in goaf, the air permeability coefficient in x and y direction is the same, K_x=K_y; p is the sum of static pressure and velocity pressure, Pa; α is the coal seam pitch, degree; v_x、v_y is the seepage velocity in x, y direction; ρ_g is the density of the gas in goaf, kg/m^3.

As shown in Fig. 2, the Γ_1 boundary was the air pressure boundary conditions; Γ_2, Γ_3, and Γ_4 air was the air quantity boundary conditions in which the air leakage quantity is zero.

(2) The oxygen concentration field equation of goaf is set up based on the basis of mass conservation law and fick's law:

$$v_x \frac{\partial c}{\partial x'} + v_y \frac{\partial c}{\partial y'} = n d_{o_2} \left(\frac{\partial^2 c}{\partial x'^2} + \frac{\partial^2 c}{\partial y'^2} \right) - \frac{u(t)}{n} \tag{5}$$

Where, c is the oxygen molar concentration, mol/m^3; d_{o2} is the oxygen diffusion coefficient, m^2/s; n is the porosity of the caving coal-rock; $u(t)$ is the oxygen consumption rate of the caving coal-rock, mol/(s·m^3).

As shown in Fig. 2, the inlet air section on the Γ_1 [5] was the first boundary condition; the return air section of the Γ_1, Γ_2, Γ_3 and Γ_4 were the second boundary condition in which the oxygen diffusion flux is zero.

(3) The residual coal temperature field equation of goaf is set up based on mass conservation law, Fourier's law and Newton's law of cooling with moving coordinates:

$$\left\{ \frac{\partial}{\partial x'} \left(\lambda_s (1-n) \frac{\partial t_s}{\partial x'} \right) + \frac{\partial}{\partial y'} \left(\lambda_s (1-n) \frac{\partial t_s}{\partial y'} \right) \right\} - K_e S_n \left(t_s - t_g \right) + q(t) = v \frac{\partial}{\partial x'} \left[\rho_s C_s (1-n) t_s \right] \tag{6}$$

Where, λ_s is the solid particle thermal conductivity of the caving coal-rock, J/(m·s·K); t_s is the solid particle temperature, K; t_g is the gas temperature of the porous in the caving coal-rock, K; K_e is the convective heat transfer coefficient between the solid particle and the gas in the caving coal-rock, J/(m^2·s·K); S_n is the specific surface area of the control unit; ρ_s is the density of solid particle, kg/m^3; C_s is the specific heat capacity of of solid particle, J/(kg·K); $q(t)$ is the heat emitted of the coal oxidation reaction within unit time, J/(mol·s); v is the average advance speed of mining face, m/s.

In the same way, the gas temperature field equation of goaf is also set up based on mass conservation law, Fourier's law and Newton's law of cooling:

$$\frac{\partial}{\partial x'} \left(\lambda_g n \frac{\partial t_g}{\partial x'} \right) + \frac{\partial}{\partial y'} \left(\lambda_g n \frac{\partial t_g}{\partial y'} \right) - \left[\frac{\partial}{\partial x'} \left(n \rho_g C_g v_x t_g \right) + \frac{\partial}{\partial y'} \left(n \rho_g C_g v_y t_g \right) \right] + K_e S_n \left(t_s - t_g \right) = 0 \tag{7}$$

Where, λ_g is the gas thermal conductivity, J/(m·s·K); C_g is the specific heat capacity of the gas, J/(kg·K).

As shown in Fig. 2, the inlet air section of the Γ_1 was the first boundary condition; the return air section of the Γ_1, Γ_4, Γ_5, Γ_6, Γ_7, Γ_8, Γ_9 and Γ_{10} was the second boundary condition in which the heat flux is zero.

4. The model for calculating

The finite volume method [11] is adopted to solve the spontaneous combustion model. Firstly, the calculating range of the model was defined, and then the calculated region was grid partition. According to the finite volume method, the model and the corresponding boundary conditions were discretization to get the node equations of pressure, oxygen concentration and temperature. Finally the computer program was compiled to solve the node equations.

5. The simulation results and analysis

The working face of Tangshangou Coal Mine was taken as an example for the solution. The depth of goaf was 450m, the length of working face was 200m, the advancing speed was 2.8 m/d, the ventilation resistance was 25Pa, the inlet air temperature was 22℃, the average thickness of residual coal was 0.8 m which the density was 1420kg/m^3 and the specific heat is 1200J/kg·℃.

(1) The oxygen concentration distribution in goaf

The solution data were treaded by post-processing software to get the oxygen concentration distribution map under non-Darcy seepage, which was shown in Fig. 3.

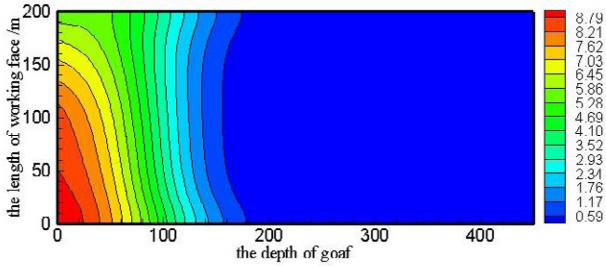

Fig. 3. The oxygen concentration distribution in goaf

In Fig.3, the highest oxygen concentration was in the air-inlet side, which was greater than 8.79 mol/m^3. And then decreased gradually in x and y direction. When arrived at the depth of 155m in goaf, oxygen concentration was 0.6 mol/m^3. After the depth, the oxygen concentration was almost approaching to zero, which couldn't support the residual coal oxidation. Therefore, the depth of 155m in goaf is the partition line to divide spontaneous combustion zone and suffocative zone. The reason for this fact is that the porosity in goaf near the working face was so larger, which caused air leakage volume bigger, that the oxygen concentration was high. As the goaf extension, the porosity was smaller and smaller for the caving coal-rock being compacted. When exceeded certain depth in goaf, the air leakage volume was approximating zero, and the oxygen concentration reached the minimum value, not in the change.

(2) The residual coal temperature distribution in goaf

In the same way, the residual coal temperature distribution map in goaf was shown in Fig. 4.

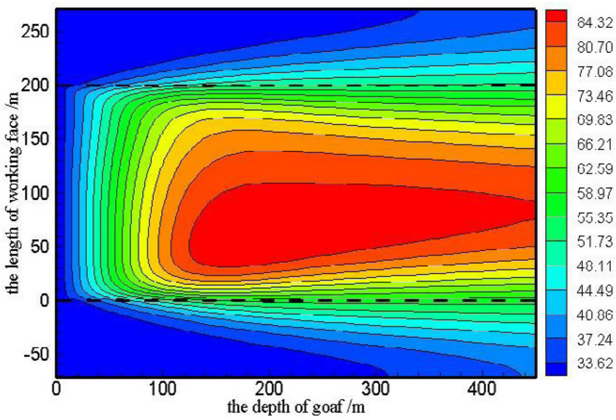

Fig. 4. The residual coal temperature distribution in goaf

In y direction, the area between 0m and 200m was the goaf; the areas between -75m-0 and 200m-275m were the protective coal pillar. Known from the Fig.4, i) the residual coal temperature in the goaf near the working face was lower, and reached the maximum 84℃ in 180m in depth, then began to decline. This is because the oxygen concentration was high in the front part of the goaf, the reaction of coal and oxygen was accelerated and more heat was released. However, most of the heat was taken away by leakage air, coal temperature rose slowly; When arrived at a certain depth in the goaf , where had good heat storage conditions and the air leakage was small, so the temperature lifted quickly; When the temperature reached and exceeded the peak, the residual coal was in suffocative zone, where the oxygen concentrations was very low, the residual coal was no longer oxidized to release heat, the coal temperature began to fall; ii) the high temperature areas were near to the air-inlet side, and the temperature gradient near to the air-inlet side was much bigger than that near to the air-return side, which conformed to present situation that the spontaneous combustion in goaf more occurred in the air-inlet side. This is because the oxygen concentration in the air-inlet areas was higher, and then the residual coal was oxidized to release more heat. So the temperature near to the air-inlet side was higher, and the temperature gradient was bigger.

6. Conclusions

1) This paper studies the non-Darcy seepage rule of broken rock, establish the spontaneous combustion mathematical model based on the non-Darcy seepage and compile a calculating software for the model;

2) The software is used to get the oxygen concentration distribution map and the residual coal temperature distribution map under non-Darcy seepage. The main conclusions: i) when exceed a certain depth, the oxygen concentration in goaf is almost zero; ii) the high temperature areas in goaf are near to the air-inlet side and the temperature gradient near to the air-inlet side is bigger. The results are of theoretical and practical significance to prevent spontaneous combustion in goaf;

3) According to the oxygen concentration distribution, the goal of Tangshangou Coal Mine is divided into spontaneous combustion zone and suffocative zone, and the partition line is at the depth of 155m in goaf.

Acknowledgements

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